CURRENT PROGRESS IN COAL-WATER SLURRY BURNER DEVELOPMENT

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INTRODUCTION

There has been significant interest in recent years in development of domestic fuels which could displace those presently imported by U.S. industry. Because of the large quantity of fuel consumed by the electric power generation industry, much of this interest has been focused on fuels to replace oil and gas combusted in existing utility boilers. Many of these efforts have focused on the use of coal as the replacement fuel since it is the United States' most abundant fossil fuel.

Unlike oil, coal cannot be easily nor inexpensively refined into a consistant definable fuel. Every coal type is different in combustible properties as well as mineral matter content and composition. Unfortunately, these are two key parameters which significantly influence the determination of a particular coal's successful application as a replacement fuel in an existing utility boiler. Successful application also depends on several other key economic factors as well; boiler derating, differential fuel savings between the presently used fuel and the candidate alternate fuel, and lastly, the resulting payback period over which the utility must amortize the cost of converting to the new fuel.

Figure 1 shows the relationship of these economic parameters. If one considers seven (7) years a reasonable payback period, Figure 1 illustrates that, with realistic unit deratings of up to 25%, a differential fuel cost of between $1.00 and $2.00 per million BTU's must be achieved to make conversion economic. This delicate economic balance is the very reason utilities have been slow to accept coal/oil slurries as a viable alternative to oil alone. With the nominal cost of oil at approximately $6.00/MMBTU and the nominal coal price at $2.00/MMBTU, and the practical amount of coal that can be mixed with oil limited to about 50% on a mass basis, the raw products alone are about $4.00/MMBTU without any allowance for slurry preparation. With this narrow differential in cost, many utilities are unwilling to risk conversion of operating units to this new fuel.

Because of the marginal economic incentive of coal/oil slurries, interest has shifted to a relatively new potential conversion fuel-coal/water slurry (CWS). Coal/water slurries have the distinct advantage of requiring no oil and therefore the potential differential in fuel cost over operation on oil alone can be much greater than that with coal/oil slurries. Coal/water slurries have several possible technical limitations, however, which must be reconciled before they can be considered as a viable replacement for oil or gas in utility boilers.

One of the concerns which must be addressed is the development of an atomizer that will properly atomize this new fuel. A problem that the atomizer development engineer faces is that most CWS fuels under development today have been designed to maximize coal content and fuel stability (i.e., minimization of settling). From an economics and transportation standpoint this approach makes sense but results in a fuel which maybe viscous, and therefore difficult to effectively atomize. If a slurry cannot be economically atomized it will not be a viable commercial fuel. Therefore, the successful CWS fuels will have to have both acceptable storage stability and rheological properties to permit good atomization with realistic levels of atomizing assist fluid.

Other concerns, in addition to rheological fuel properties, are fuel ignition and warm-up requirements, burner stability and turn-down, and carbon conversion and thermal efficiencies. Most CWS testing to date has been in small laboratory facilities of 1 to 4 MMBTU/hr and, in general, results have been poor, compared to that which must be achieved if CWS fuels are to be accepted as a viable replacement fuel by utilities. Test furnaces have required extensive preheat, burner turn-down has been extremely limited and carbon conversion efficiencies have, at best, been in the high 80% to mid 90% range(1,2,3).

In addition to these potential problems with CWS combustion, Figure 1 indicates that unit derating can play a significant role in dictating the success of a fuel conversion. For this reason coals to be used for CWS's must either be carefully selected on the basis of their original ash characteristics or they must be beneficiated (i.e., cleaned of mineral matter) to minimize furnace slagging/fouling and erosion such that significant boiler deratings will not be encountered.

CWS BURNER DEVELOPMENT

This paper is a progress report on a joint program between Combustion Engineering (C-E) and the Electric Power Research Institute (EPRI) to develop and demonstrate a commercial scale CWS burner which meets reasonable commercial success criteria. As such, a burner is presently being developed which meets the following constraints:

1. Permits ignition in a cold furnace with conventional ignition equipment.

2. Operates stably over a 4 to 1 turndown range without supplemental ignition fuel.

3. Employs fuel and atomizing media pressures that are obtainable with commercially available equipment.

4. Requires atomizing media to fuel mass flow ratios similar to those used for oil.

5. Produces carbon conversion efficiencies comparable with oil (i.e., high 90% range) at acceptable excess air levels (i.e., 20-30%) and reasonable air preheat temperatures (i.e., 250 to 400°F) over the full load range of the burner.

To achieve these goals C-E is using a proven three step firing system development approach.

1. Development of a CWS atomizer using C-E's Atomization Test Facility.

2. Development of an aerodynamically sound burner register using C-E's Burner Modeling Facility.

3. Integration of the developed atomizer and burner register, and optimization of the CWS firing system's combustion performance at a commercial firing scale of 80/MMBTU/hr in C-E's Full Scale Burner Test Facility.

This paper does not contain all combustion data which was still being analyzed at the time this paper was prepared; the combustion data is, therefore, preliminary.

FUEL PREPARATION AND CHARACTERIZATION

The fuel required for this development program was donated by Advanced Fuels Technology (AFT), a Gulf and Western Company. The coal used was a Clearfield County, Pennsylvania bituminous, selected by EPRI. The required coal was cleaned, prior to testing and slurry preparation, at EPRI's Coal Cleaning Test Facility in Homer City, Pennsylvania. A simplified flow schematic of the cleaning process used is shown in Figure 2, and the analysis of the cleaned coal is shown in Table 1.

Coal to be cleaned by EPRI's test facility is initially crushed to a nominal 3/4" x 0 size and then processed through a multistage "desliming screen". The first screening stage removes oversized material (+3/4") from the process steam. The second stage removes coal which is of a 3/4" x 28 mesh size. This is the main process steam. Separated material (+3/4" and -28 mesh) is collected in a refuse pile for future independent treatment. The main coal stream is then processed through two stages of "heavy media cyclones" followed by a "sieve bend & screen" to separate the clean coal from the refuse portion. The separation principle is based on the mass density differences between the coal (which is relatively light) and the high mineral matter fractions (which are relatively heavy). After passing through these steps the coal is passed through a "basket centrifuge" to be partially dewatered. At this point the coal is considered "cleaned". It is metered by a weigh belt and is passed to a storage pile.

The high ash refuse obtained from the separation processes is collected in a refuse pile for disposal and/or future reprocessing. Process fluids are separated from the refuse and cleaned coal streams, and collected for reuse. For the special purpose of generating a very low ash coal for this testing program, refuse material was not reprocessed and combined with the initially cleaned main coal stream as would be the normal procedure.

In all, approximately 150 tons of cleaned coal were prepared for this program. Approximately 40 tons of the cleaned coal was reserved for base coal testing to establish a meaningful reference base for comparison to CWS combustion performance. The balance of the coal (approximately 110 tons) was processed, by AFT, into a nominal 70% solids CWS of predetermined specifications. These specifications were developed jointly by C-E and AFT to assure the maximum probability for combustion success through careful attention to oversized particles and minimization of fuel viscosity. The developed fuel specifications are presented in Table 2 with an analysis of the produced CWS. A schematic of AFT's CWS preparation system is shown in Figure 3.

Figure 4 shows a typical viscosity profile of the CWS which was obtained using a Haake Rotovisco viscometer. As can be seen in Figure 4, the CWS exhibited Newtonian to slightly pseudoplastic behavior (i.e., viscosity remains constant or decreases slightly with increasing shear rate). From an atomization standpoint, pseudoplasticity is desirable since the viscosity decreases at the high shear rates encountered within the atomizer. A Newtonian behavior is also acceptable since the viscosity remains constant with increasing shear rate. Dilatent behavior is not acceptable since the viscosity increases with increasing shear rate and would lead to poor atomization.

It is important to note that in order for CWS to attain commercial acceptance, a balance must be achieved between the high static viscosity required for transport and storage stability and the rheological properties required for atomization and combustion. Also, rigid control of particle top size and stringent quality control by the slurry manufacturers is necessary to insure a consistant supply of usable CWS.

FUEL SHIPPING, STORAGE AND HANDLING

The CWS prepared by AFT was shipped to C-E's Kreisinger Development Laboratory (KDL) at Windsor, Connecticut in conventional pressurizable tanker trucks. Although the tankers used had volumetric capacities of approximately 6500 gallons, five tankers were needed to transport the required 21,000 gallons of slurry because each was limited to a capacity of only about 4,200 gallons due to the legal over-the-road weight limit of 45,000 lbs. Photographs 1 and 2 show a tanker truck arriving at C-E and being unloaded, respectively.

C-E's Alternate Fuels Handling Facility (AFHF) is shown schematically in Figure 5. This facility is comprised of a 15,000 gallon storage tank, a 2500 gallon day tank, an homogenizer and several pumps, filters and heaters configured to handle slurry-type fuels. Figure 6 shows the arrangement of those components of the AFHF specifically utilized for the CWS testing program.

Preliminary testing indicated that the tanker trucks could be effectively unloaded two ways. One manner was by pumping the CWS from the tanker in an unpressurized state. A Tuthill model 120A pump was used and permitted unloading to the AFHF 15,000 gallon storage tank at a rate of 12-15 gpm. The second procedure, which was used for the balance of the required unloading, was to by-pass the pump and unload the fuel by pressurizing the tanker to 30 psig. At this pressure, the tankers were unloaded at an average rate of 50-70 gpm, or 1-1½ hours per 4,200 gallon tanker load.

As was previously mentioned, a total of five tanker truck loads of CWS were received for the test program. The initial two tankers received contained CWS of proper specification (see Table 2) and appeared to maintain storage stability and slurry uniformity over a period of several weeks with only occasional recirculation using the Tuthill pump. A portion of the fuel from these initial two tankers was used for the atomizer development phase which will be discussed later.

These were some off-spec. changes in the third tanker shipment of fuel which affected rheological properties of previously shipped fuel as well as the fourth tanker load of CWS fuel. On-site adjustments by G&W personnel combined with increased fuel circulation at C-E permitted testing to continue. The last tanker of fuel was significantly higher in viscosity than the previous fuel batches; this required higher fuel supply pressures to achieve the same mass flow rates as the previous fuel shipments.

CWS ATOMIZER DEVELOPMENT

The development of an atomizer for CWS was essential to the developmental success of the C-E/EPRI CWS burner. The purpose of the atomizer is to fragment the CWS fuel stream into readily combustible droplets. The size, velocity and trajectory of these fuel droplets is a function of both the atomizer's design and the burner's near-stream aerodynamics, and directly affects burner performance in terms of flame length, stability and carbon burnout.

In the course of development, careful consideration was given to both the CWS atomizer's generic design as well as its specific geometric dimensions. Of generic atomizer designs reviewed by C-E, the "Y" jet configuration (Figure 7) appeared to have the greatest potential for success with CWS. Two properties of CWS were identified as potentially problematic to effective atomization. These were its erosive nature and high viscosity (Figure 4). "Y" jet type atomizers utilize pressurized atomizing media (superheated steam or compressed air) to initiate fuel stream breakup through high shear turbulent mixing of the atomizing media and fuel streams. This "Y" jet atomization principle has been shown(4) to be effective for the atomization of viscous fuels and thus would be potentially successful with CWS. Secondly, because of the atomizer design's simple geometry, with no tortuous paths, it permits fabrication with erosion resistant materials (Figure 8).

Combustion Engineering has extensive experience in "Y" jet atomizer design and has developed a computer design code and a full scale Atomization Test Facility (ATF) to assist in "Y" jet atomizer design development. These were utilized in a three step approach which resulted in the successful development of a CWS atomizer. These steps were:

1. Theoretical identification of critical atomizer geometric dimensions based on fuel properties and atomizing media considerations.

2. Preliminary ATF testing and performance optimization of the theoretical atomizer design.

3. Detailed ATF performance characterization of an optimum atomizer design over a matrix of operation.

ATOMIZER TEST FACILITY

C-E's Atomizer Test Facility (ATF) is designed to quantitatively characterize the atomization quality of full scale (10 gpm) burner atomizers. The facility is uniquely configured to obtain droplet size distribution and droplet ballistics (velocity and trajectory) information from fuel sprays.

The facility operates in a cold flow (non-combustion) mode and has provisions for studying both conventional liquid and slurry fuels. Provisions for slurry fuels include a 700 gallon transportable fuel tank for storing and heating fuels prior to ATF testing. The tank is equipped with a mixer and recirculation system to minimize potential slurry solids stratification.

A schematic of the Atomization Test Facility is shown in Figure 9. The actual facility is presented in Photo 3.

Test atomizers are centrally located in the spray chamber and spray vertically down, thus minimizing the effect of gravity in atomization droplet ballistics measurements. Also, a constant velocity profile (10 ft/sec) airflow passes by the atomizer during testing to prevent potential droplet recirculation which would otherwise bias droplet trajectory information. Large windows in the spray chamber permit optical access across the atomized sprays. Optical spray diagnostic equipment is located on the two benches as shown. Once data is obtained from the spray, the fuel droplet-laden air flow is demisted and exhausted from the facility. The collected fuel is then removed for reuse or disposal.

OPTICAL DIAGNOSTIC TECHNIQUES

Two optically-based techniques are utilized by C-E in the ATF to quantify spray quality. A laser diffraction technique is used to determine the spray droplet size distribution and a high speed double spark photographic technique is utilized to define droplet velocity and trajectory.

The laser diffraction technique is based on the Fraunhofer diffraction of a parallel beam of mono-chromatic light by moving of stationary droplets or particles(5). A Fourier Transform lens yields a stationary light pattern from the light diffracted by the particles. A multi-element photo-electric detector located at the focal plane of the Fourier Transform lens produces an electrical signal analogous to the diffracted light. A mini-computer compares this signal with the derived signal based on a Rosin-Rammler model which continuously modifies the mean diameter and exponent parameters until a best fit is obtained(5). Percentage weight fraction and normalized percentage number density are then calculated from the best fit model.

Figure 10 shows a schematic of the laser diffraction apparatus. The laser is the monochromatic light transmission source and the diffracted light is received and analyzed by a Fourier Transform lens, a photoelectric detector, and a mini-computer. Note, the optical probe included in the schematic is used to alleviate measurement errors in dense fuel sprays.

The optical arrangement for the high speed double spark photographic technique is depicted schematically in Figure 11. Two spark-gap light sources are located on one side of the facility. Each source produces one intense, short duration (1 microsecond) flash of light. These flashes of light are directed through the atomizer spray by a lens system and into a camera lens located on the opposite side of the facility. The camera lens is focused on a specified plane within the spray field (object plane). Silhouette images of the droplets located in the camera's object plane and field of view are recorded on film.

The two flashes produce a double exposure silhouette photograph of the droplets. Accurate droplet velocity information is then obtained by measuring the distance traveled by an individual droplet between exposures with knowledge of the time interval between flashes. Similarly, droplet trajectory is determined by observing the direction of travel for individual droplets.

INITIAL CWS ATOMIZER DESIGN

The CWS atomizer was designed in part by the application of a computer code previously developed by C-E to predict "Y" jet atomizer atomization quality (in terms of spray droplet mass median diameter) with heavy fuel oils. This program code estimates atomizer performance as a function of critical fuel properties and atomizing media constraints. These include, fuel viscosity, atomizing media density, and atomizing media to fuel mass flow. C-E utilized this code to predict CWS atomization quality. The predictions, in conjunction with pressure drop calculations, fluid momentum considerations, and geometric correlations obtained in previous atomizer development efforts, resulted in the identification of specific atomizer dimensions; these are shown in Figure 7. The target CWS atomization quality was that which is typical for firing residual fuel oil using a "Y" jet atomizer. Based on previous tests conducted in the ATF(6), a spray mass median diameter of 120 microns or less is characteristic of effective residual oil atomization. Note, that this droplet diameter is significantly larger than that of the individual coal particles of conventionally ground coal for P.C. firing.

This phase of CWS atomizer design actually yielded two distinctly different "Y" jet atomizer geometries with similar performance, given identical fuel and atomizing media conditions.

PRELIMINARY ATF TESTING

Preliminary ATF testing involved a comparative performance evaluation of the two "Y" jet atomizer geometries identified during initial CWS atomizer development. The laser diffraction system was utilized for this effort. Each atomizer nozzle design was tested at 100%, 50%, and 25% of maximum firing rate over a wide range of atomizing media to fuel mass flow ratios ($.06 \leq A/F \leq 1.1$). Compressed air was used as the atomizing media. For these tests, CWS and atomization air were maintained at ambient temperature. Data obtained from these comparative tests is presented in Figures 12, 13, and 14.

At 100% load, nozzle design 5A produced finer sprays than nozzle 5B at A/F ratios greater than 0.17. Operation with such high atomizing media consumption is undesirable, however, because it is a parasitic energy loss, and thus negatively impacts boiler economics. Nozzle design 5B consistantly produced a finer spray than design 5A at more favorable A/F ratios of 0.17 and below.

At both 50% and 25% load, nozzle design 5B produced equivalent or finer CWS sprays than nozzle design 5A at given A/F ratio settings. Based on these tests, nozzle design 5B was chosen for further detailed atomization quality optimization and characterization.

DETAILED CWS ATOMIZER TESTING

Detailed parametric testing of the optimum atomizer (design 5B) provided insight into the key operating parameters which influence atomizer performance. Parameters studied included:

- Atomizing media to fuel mass flow ratio
- Fuel mass flow rate
- Fuel temperature
- Atomizing media temperature

Atomizing Media to Fuel (A/F) Mass Flow Ratio

The ratio of atomizing media to fuel mass flow was found to have a significant effect on the performance of the CWS atomizer. Data depicted in Figure 15, taken at 100% load, indicates that above an A/F ratio of 0.17, the spray mass median diameter remains constant. A gradual degradation in atomizer performance occurred between A/F ratios of 0.17 and 0.06, and rapidly degraded below an A/F ratio of 0.06. Similar trends were noted at 50% and 25% load.

The spray droplet size distribution obtained on CWS at full load was similar to that obtained through previous testing of "Y" jet atomizers spraying fuel oil. The optimum range of A/F ratios for the CWS atomizer appeared to be between .08 and .14, which are also typical of those required for fuel oil atomization.

Effect of Slurry Temperature

The effect of CWS temperature on atomization quality is presented in Figure 16. Atomizing air temperature was held constant at 95°F during these tests. CWS was tested at 95°F (ambient temperature) and at 150°F over a range of atomizing media to fuel mass flow ratios.

The data indicates that a slight decrease in spray mass median diameter (MMD) of approximately 10% occurred when the particular CWS tested was preheated prior to atomization. The reduction in MMD could possibly be attributed to a reduction in fuel viscosity at elevated temperature.

The slight decrease in MMD did not appear to provide sufficient justification for preheating the fuel in the combustion phase of the testing.

Effect of Atomizing Air Temperature

The effect of atomizing air temperature on atomization quality is presented in Figure 17. CWS temperature was held constant at 95°F during this series of tests.

The data indicates that a reduction in MMD, of approximately 10%, can occur by preheating the atomizing air. Again, however, this reduction would not appear to be significant enough to warrant preheating the atomizing air.

Effect of Slurry and Air Temperature

The combined effect of both elevated CWS and air temperature on atomization quality is shown in Figure 18. It was concluded from ATF testing that heating both slurry and air produced a finer spray yet than either fluid heated individually.

This information would be useful should a particular burner/atomizer combination prove to perform marginally on a specific CWS. Preheating both fuel and air may shift the droplet size distribution down to within a range capable of improving combustion performance. The improvement in performance would have to be evaluated against the increased capital equipment costs and energy costs incurred when preheating these fluids.

Overall, the performance of the developed CWS atomizer, with ambient CWS and air temperature, was quite similar to conventional C-E "Y" jet atomizer performance and fuel oil. For this reason, for the combustion evaluation of CWS, fuel was supplied at ambient temperature and atomization air was not heated beyond the compressor's nominal delivery temperature of 160°F.

Droplet Ballistics

Droplet velocity and trajectory information, obtained through the use of the high speed double spark photographic technique, indicated that CWS droplet velocities were similar to those obtained for conventional fuel oils. Velocities ranged between 2 and 24 meters/second, at an axial downstream distance from the atomizer of 140 nozzle diameters. Droplet trajectories tended to follow predictable streamlines of a freely expanding jet.

Droplet velocity is a strong dependent function of droplet diameter for both oil and CWS.

Since the velocities obtained for both oil and CWS were similar, no droplet ballistics related changes in burner aerodynamic design appeared necessary.

BURNER REGISTER DEVELOPMENT - COLD FLOW MODELING

A full-scale model of the proposed burner register was fabricated and flow model tested under isothermal conditions. The purpose of this work was to confirm that the register design exhibited satisfactory aerodynamic characteristics over the full range of air flows expected to be used during combustion operation. An important and necessary aerodynamic characteristic for good flame stability is the existence of a strong well developed recirculation zone at the burner throat. In the C-E CWS burner, the recirculation zone is established through combustion air swirl and a divergent burner throat. These are well known methods of inducing a recirculating flow and have been used commercially for some time(8,9).

Flow visualization techniques were employed by C-E and confirmed the CWS register design's satisfactory aerodynamics over a range of simulated operation. Figure 19 shows, schematically, the model used and the observed recirculation zone boundary.

BURNER DESCRIPTION

The C-E coal-water slurry burner is a swirl stabilized unit configured for tangential firing and is shown schematically in Figure 20. The basic burner design is adaptable to wall firing with suitable modifications. The principle elements of the burner system are: a refractory-lined divergent throat, a combustion air swirler through which a portion of the combustion air is passed, auxiliary air nozzles, above and below the burner, through which the balance of the combustion air is ducted (unswirled), and a slurry gun with an atomizer.

The purpose of the refractory-lined divergent throat is to increase the mass recirculation ratio and therefore to stabilize the flame both aerodynamically and thermally. The swirled combustion air stabilizes the flame and contributes to high combustion efficiency. The atomizer's production of relatively fine CWS droplets combined with the overall burner aerodynamics has yielded acceptable stability, over a to 1 load turndown range. Acceptable combustion efficiencies have also been demonstrated with this burner/atomizer combination. Preliminary data documenting this performance will be covered in the following section.

COMBUSTION TESTING

The combustion performance of the CWS burner was optimized and extensively evaluated at a commercial load which ranged from 20 to 80 MMBTU/hr. These tests were conducted in C-E's Full Scale Burner Facility (FSBF). The burner's combustion performance was parametrically investigated on both CWS and parent coal so that a meaningful combustion evaluation of CWS could be made via comparison to a known reference fuel. Test condition matrices for each fuel (shown in Tables 3 and 4) were designed to parallel one another so that direct test-by-test comparisons could be made. Test variables were; firing rate, excess air level, combustion air preheat temperatures, and also, for CWS, atomization air/fuel mass ratio. Data were obtained, depending on specific test conditions, of numerous independent parameters. These were gaseous emissions (CO, CO_2, NO_x, SO_2, and O_2), heat flux profile, calculated combustion efficiency, flame quality, fuel flowrate/temperature/pressure, combustion air flowrates/temperatures/pressures, atomization media flowrate/temperature/pressure, and at selected test points in-stack fly-ash sampling, which included dust loading, carbon content, particle size distribution and in-situ resistivity.

Prior to conducting these detailed combustion tests, prematrix and shakedown tests were performed to qualitatively define burner performance and to establish the probable ranges of operability. During these tests burner performance was optimized through combustion airflow distribution adjustments. Detailed parametric performance testing was then initiated once these preliminary tests indicated acceptable burner performance on CWS.

As stated previously, this paper is a progress report on C-E's CWS burner development program with EPRI. As of the date of writing (November 1982) combustion testing is complete, but detailed data analysis is still in progress. The data presented must be considered preliminary.

CWS Combustion Testing

Observed CWS flame stability and appearance was acceptable over the range of burner operation tested. In general the flame was "attached" or nearly "attached" to the burner. No major burner operability problems were noted during testing, although several items warrant mention. Because of the CWS storage tank settling problems previously discussed, fuel quality varied appreciably from test to test. Solids content varied from 67.1 to 70.0%. Some degree of combustion data scatter may be attributable to this, although data presented here was well within measurement confidence limits.

Secondly, the CWS was ignited satisfactorily in a cold, unheated test furnace using the facility's standard 5 MMBTU/hr natural gas side pilot ignitor. There was only one unusual requirement identified for ignition. This was the necessity of "prewetting" (with water) the atomizer and slurry gun prior to CWS introduction to prevent the absorption of a small but apparently critical amount of the slurry's water component. This was accomplished by inclusion of a water supply line to the fuel piping at the slurry gun. Failure to follow this procedure significantly increased the potential for nozzle pluggage during ignition.

The ignition procedure was as follows. First, a 5 MMBTU/hr natural gas side pilot ignitor was turned-on. Second, a small amount of water was passed through the slurry gun and atomizer. Next, the water was turned-off and simultaneously the CWS and compressed atomization air were turned-on, resulting in satisfactory CWS ignition. The side pilot was normally shut-off after about fifteen minutes of operation. Nominal burner firing rate for light-off was 25 MMBTU/hr and combustion air preheat of 250°F was utilized. Note, ignition was consistently achieved in the test furnace while in a cold and unpreheated state. However, because the furnace was lined with a thin layer of refractory blanket to simulate normal furnace heat losses and hence actual furnace outlet temperature, the furnace wall temperature may have risen at a somewhat higher rate than would be seen in an actual clean cold boiler. Thus the time that the ignitor is required to be on for a field application may be somewhat longer than the period discussed here.

Lastly, all tests were conducted with the 70° spray angle, tungsten carbide sleeved, "Y"-jet atomizer described under atomizer development. Approximately 20 hours and 100,000 lbs of slurry throughput were logged on this atomizer. The atomizer port diameters were precision measured before and after testing and indicated no measurable wear in the critical zones protected by the tungsten carbide sleeve. By comparison a carbon steel atomizer was used for prematrix testing, and while no meaningful erosion rate data could be obtained because of the intermittent and variable operation, significantly greater wear was noted in this atomizer over a much shorter period (i.e. 4 hours and 25,000 lbs. of slurry).

Parent Coal Combustion Tests

Parent coal combustion tests were conducted to provide baseline data to which the CWS combustion data could be compared. The parent coal was ground, for combustion testing, to a nominal size distribution of 70%-200 mesh which is standard for use as a boiler fuel firing pulverized coal.

Parent coal fuel injection modeled that of CWS so that meaningful fuel performance comparisons could be made. Coal was supplied in "dense phase" through a 1" ID fuel admission port to the center of a 70° diffuser cone. In this way the parent coal was "sprayed" into the furnace at the same 70° angle as that of atomized CWS. Note that the same combustion air register was used for both the parent coal and CWS tests.

Coal was supplied in dense phase with a C-E developed coal pumping, storage and supply system(10). This system permitted dense phase pulverized, parent coal, transport with transport air to fuel mass flow ratios in the range of 9 to 26. The parent coal was pneumatically conveyed from a 30 ton storage silo through an 1¼" ID hose to the FSBF firing front. Pressure drop across the transport line varied from 6 to 26 psig.

Qualitatively, the combustion performance of the parent coal was excellent. Observed flame stability and appearance was similar, but slightly better than that noted previously for CWS over the same range of operation. The parent coal burned with a bright flame which was always "attached" to the burner.

Parent coal was readily ignitable in a cold, unpreheated test furnace using the facility's 5 MMBTU/hr natural gas side pilot ignitor. Once the parent coal was ignited in a cold furnace, the side pilot could be turned-off between one and five minutes with maintained flame quality and burner stability. For CWS ignition, 15 to 20 minutes were required before the side pilot could be turned-off. C-E has previously demonstrated that a similar type of dense-phase coal burner could be dependably ignited with an electric arc discharge within 30 seconds with no supplementary ignition or stabilization source, such as the side pilot.

A discussion of the comparative combustion performances of CWS and parent coal follows.

<u>Combustion Performance Comparison of CWS to Parent Coal</u>

To reiterate, both CWS and parent coal burned with bright, stable, "attached" or nearly "attached" flames over the burner load range tested. It was observed that as burner load was increased, from 20 to 80 MMBTU/hr, the axial flame length increased, but stability and attachment to the burner were maintained.

Figure 21 compares the carbon conversion efficiency of parent coal and CWS, as a function of excess air level at full load (80 MMBTU/hr). It can be seen that, at this load, parent coal combusted with 99+% carbon conversion efficiencies, and the CWS combusted with efficiencies about 1% less.

While the trends indicated in this figure are typical of those encountered at the other loads tested, preliminary data analysis indicates differences in carbon conversion efficiency of as much as 4% between parent coal and CWS existed at some test conditions. For most test conditions, however, carbon conversion efficiencies for CWS were diminished no more than 1 to 2 percent below that of the parent coal.

A comparison of carbon conversion efficiency as a function of burner load, between CWS and parent coal, at a constant 30% excess air level is shown in Figure 22. This figure reiterates the efficiencies noted in Figure 21. Parent coal was combusted with 99+% carbon conversion efficiency and again the CWS burned with approximately 1% lower efficiency over the load range presented. Note also that for each fuel, carbon conversion efficiency did not significantly vary as a function of load (40 to 80 MMBTU/hr) at 30 percent excess air.

Figure 23 illustrates the importance of good CWS atomization with regard to carbon conversion efficiency. All other conditions remaining the same, atomizer air to fuel mass ratio (A/F) was varied about an optimum value of 0.11 (identified during cold flow atomization development). Figure 23 indicates that below this optimum value carbon conversion efficiency drops off rapidly, while operation at higher A/F ratios yields no apparent efficiency change. This phenomena is in agreement with cold flow atomization results (Figure 15) which indicated rapid increase in mean atomized droplet size (diminished atomization quality) as A/F decreases from optimum and no improvement in atomization quality as A/F increased from optimum.

The resistivity values of the CWS and parent coal fly ashes, measured in-situ, are given in Table 5. These measurements indicate the fly ashes apparent collectability by electrostatic precipitation. What is important to note from Table 5 data is the lack of significant difference between the CWS and the parent coal fly ashes. This implies that, at least for this specific case, the slurrying process had no significant effect upon fly ash resistivity (i.e., collectability). Fly ash collectability by ESP is also a function of particle size. Fly ash particle size distribution results have not yet been analyzed, however, and are necessary before any final statements can be made with regard to the comparitive collectabilities of the CWS and parent coal fly ashes.

In conclusion, although the data obtained indicates satisfactory carbon conversion efficiencies for CWS, other factors influencing overall plant efficiency must be considered in dictating the viability of conversion to CWS. For instance, a latent energy penality is incurred due to the water component in the CWS. For the CWS tested (30% water by weight) a latent loss of 2.44 percent thermal efficiency would result with stack gas exit temperatures of 212°F; higher stack gas exit temperatures, required above sulfur-related dewpoints, would result in proportionally higher latent thermal losses. Furthermore, based on C-E's experience in handling fuels on a large laboratory scale, coal/water slurries are less efficient than oil from a parasitic power consumption standpoint for storage, transport and atomization (see Table 6). These factors and others must be evaluated in determining the applicability of a given CWS conversion.

SUMMARY

A burner/atomizer combination has been developed by Combustion Engineering which will burn CWS with satisfactory combustion efficiency over a wide load range. This firing system was developed using a three step approach to the problem. These steps included: 1) Atomizer development and optimization using an advanced C-E developed computer program and state-of-the-art spray measurement techniques, 2) Cold flow burner modeling to optimize the burner register's aerodynamic flow field, and 3) Full scale combustion matrix testing firing coal water slurry and its parent coal to characterize combustor performance and gather emissions data.

The preliminary results of this project show that the developed atomizer effectively atomizes high viscosity CWS (up to 2800 CPS). Measured atomization qualities and atomizing media consumption rates were similar to those measured for heavy fuel oil. Spray droplet size distributors were equivalent to those of a pulverized coal grind (with 30% inherent moisture) ranging between 115 and 150 mesh. Measured droplets were still significantly larger than the individual coal particles in the slurry.

Atomizer geometry was found to significantly influence atomization quality. However, preheating CWS prior to atomization (to reduce viscosity) did not have a great influence and yielded little improvement. Preheating the atomizing air also proved to be of limited value. However, because atomization did improve slightly with increased atomizing air temperature, the elimination of air compressor intercoolers would benefit atomization at no additional cost. The combined effects of preheating both slurry and air prior to atomization was found to be greater than either influence alone, however the improvement in atomization quality did not seen significant enough to meret the additional energy penality. For combustion testing, CWS was not heated and atomizer air was not heated beyond the compressor's delivery temperature.

The preliminary combustion testing results indicate that, with the proper combination of burner and atomizer design, coal-water slurry can be successfully burned with carbon conversion efficiencies in the range of 96 to 99+%. This compares with a consistant 99+% carbon conversion efficiency for the base coal fired under similar conditions. Additional improvements in CWS combustion efficiency may be possible through further firing system development and refinement.

This project has also successfully demonstrated that coal-water slurry could be reliably ignited in a cold furnace using conventional ignitors and low air preheat temperatures (250°F).

Although preliminary results have demonstrated satisfactory CWS combustion performance on a large laboratory scale, there are several other boiler-related areas which must be

addressed before CWS can become commercially viable. Furnace slagging, fouling and boiler derating, as well as, differential fuel costs and conversion costs must balance out favorably when compared to continuing operation on heavy oil. Detailed discussion of these factors is beyond the scope of this paper, but will dictate the ultimate viability of CWS as a boiler fuel.

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Figure 1

PAYBACK PERIOD vs FUEL COST AND DERATING
REFERENCE 7

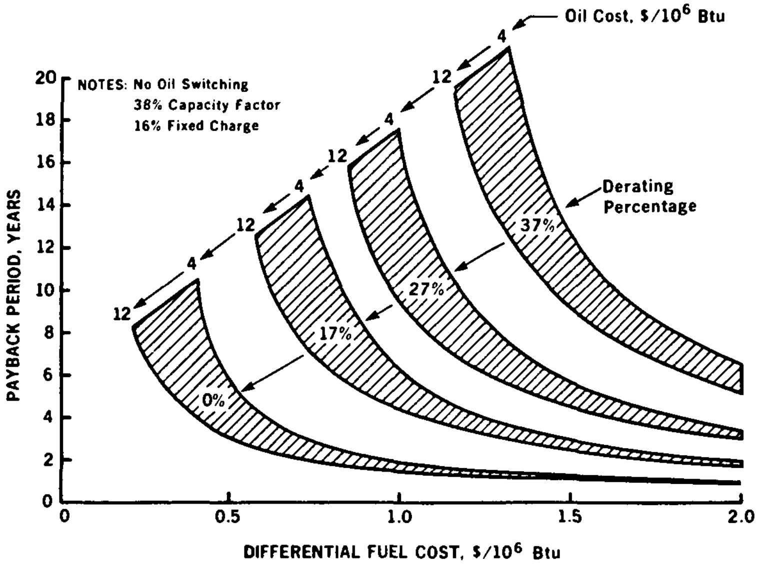


Figure 2

EPRI's HOMER CITY COAL CLEANING TEST FACILITY
SIMPLIFIED SCHEMATIC OF EQUIPMENT CONFIGURATION USED FOR PRODUCING LOW ASH COAL

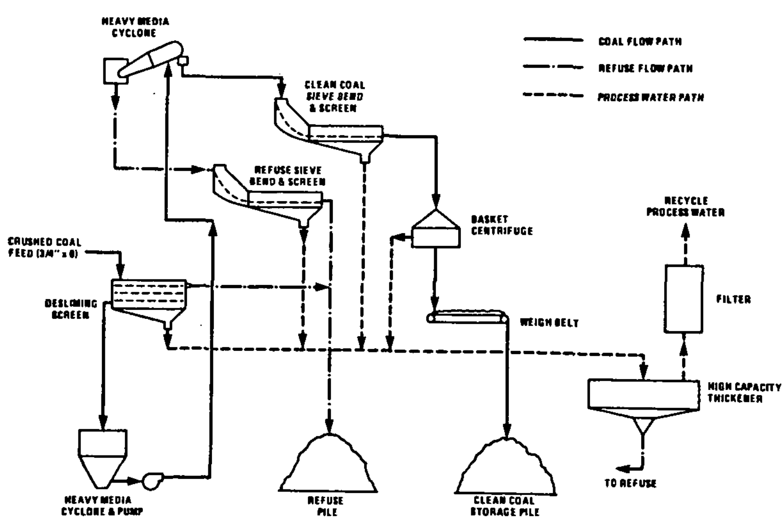


Table 1

Analysis of Parent Coal After Cleaning
at EPRI's Homer City Coal Cleaning Test Facility

	"AS RECEIVED"	"MOISTURE FREE"
PROXIMATE ANALYSIS, %		
Moisture	6.4	--
Volatile Matter	37.6	40.1
Fixed Carbon	53.1	56.8
Ash	2.9	3.1
ULTIMATE ANALYSIS, %		
Moisture	6.4	--
Carbon	74.5	79.6
Hydrogen	5.4	5.8
Nitrogen	1.5	1.6
Sulfur	.9	.9
Ash	2.9	3.1
Oxygen (diff.)	8.4	9.0
GROSS HEATING VALUE		
BTU/lb	13,790	14,730

Table 2

Coal-Water Slurry Properties
CE/AFT CWS Specification

Particle Size	100% minus 100 Mesh
Viscosity	less than 2800 Centipoise at 113 sec^{-1} and 25°C (Haake Method) Newtonian or Pseudo Plastic Behavior
Volatile Matter	Greater than 30% by weight (dry)

AFT Coal-Water Slurry Analysis

Total Moisture, %	31.0
Solids Content, %	69.0

	"AS RECEIVED"	"MOISTURE FREE"
Proximate Analysis, %		
Moisture	31.0	--
Volatile Matter	27.1	39.3
Fixed Carbon	40.1	58.1
Ash	1.8	2.6
Ultimate Analysis, %		
Moisture	31.0	--
Hydrogen	3.8	5.5
Carbon	56.1	81.3
Sulfur	.6	.9
Nitrogen	1.1	1.6
Oxygen (diff.)	5.6	8.1
Ash	1.8	2.6
Gross Heating Value		
BTU/lb	10,170	14,740

Photo 1
TANK TRUCK ARRIVING AT ALTERNATE FUELS HANDLING FACILITY WITH A LOAD OF COAL-WATER-SLURRY

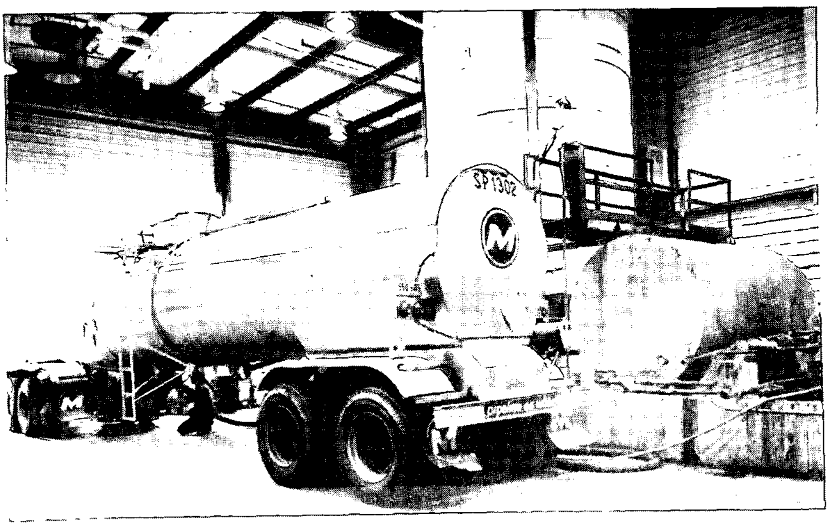


Photo 2
TRANSFERRING COAL-WATER-SLURRY FROM TANKER TO THE 15,000 GALLON STORAGE TANK

Figure 3

SIMPLIFIED PROCESS DIAGRAM
FOR BENEFICIATION/FUEL BLENDING
DEVELOPED BY AFT
(A GULF & WESTERN CO.)

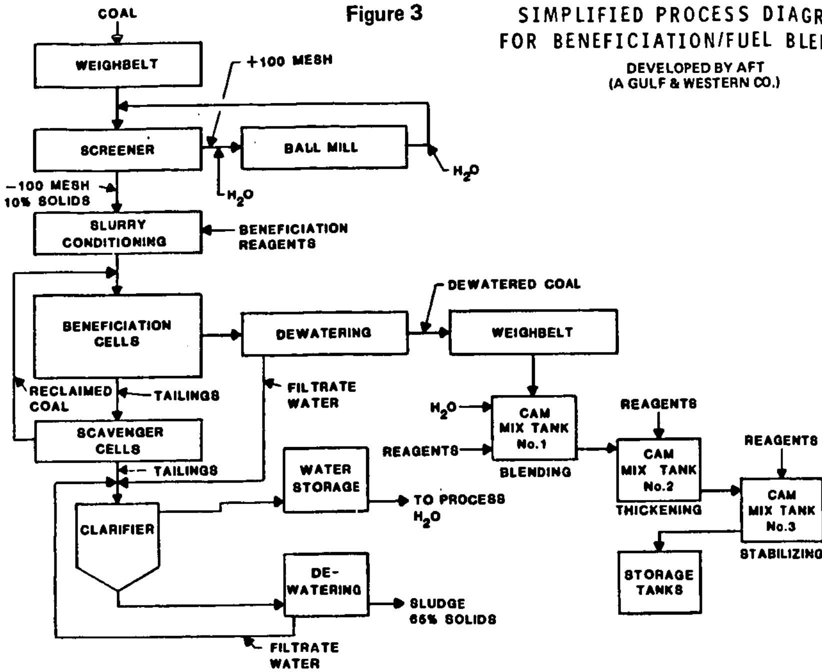


Figure 4

TYPICAL COAL/WATER SLURRY
VISCOSITY vs SHEAR RATE
DATA SUPPLIED BY AFT

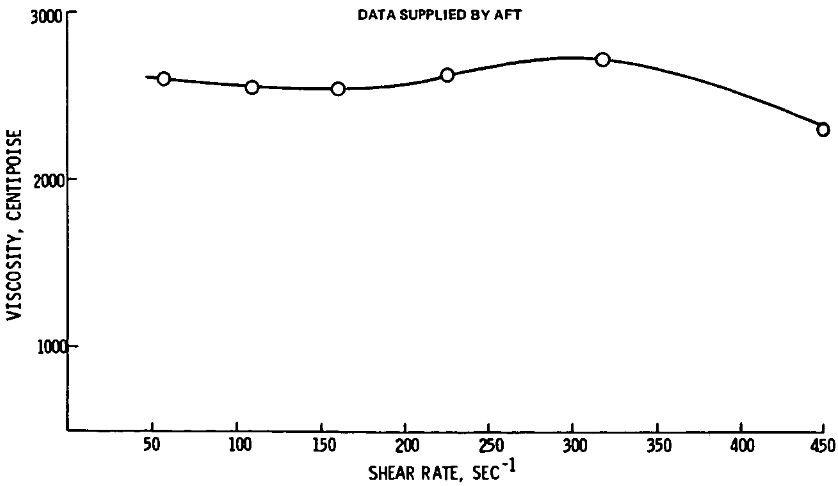


Figure 5

ALTERNATE FUELS HANDLING AND FIRING SYSTEM SCHEMATIC

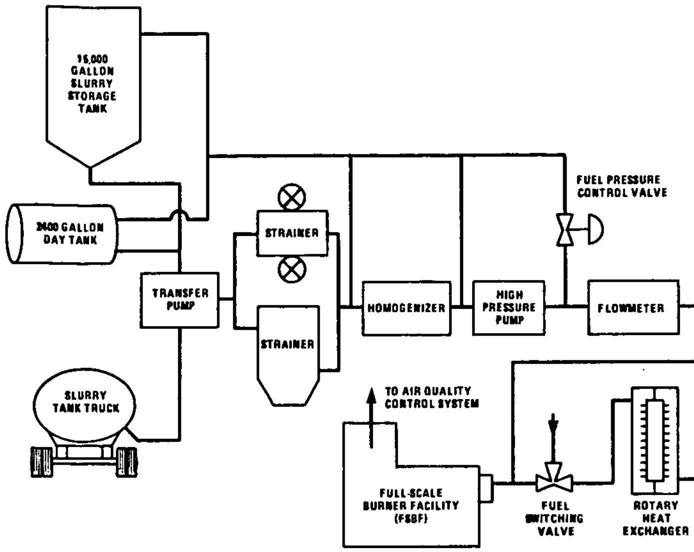


Figure 6

SIMPLIFIED COAL-WATER-SLURRY FIRING SYSTEM SCHEMATIC

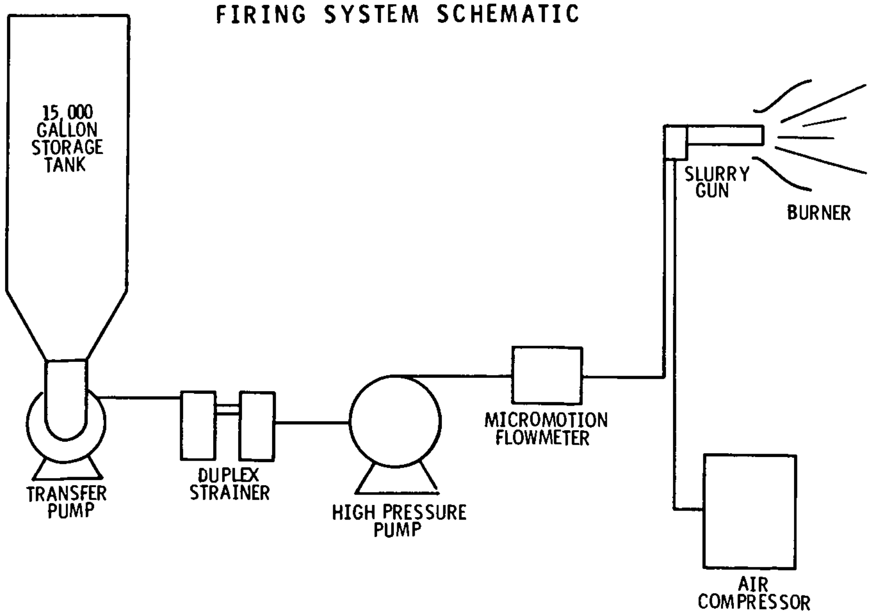
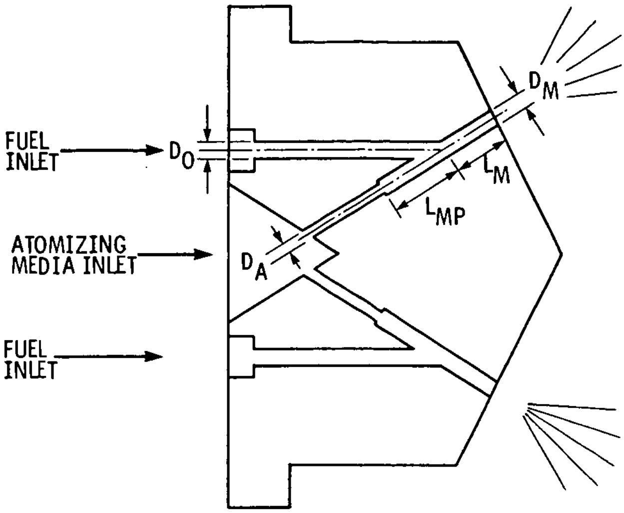


Figure 7

CRITICAL DIMENSIONS -"Y" JET ATOMIZER DESIGN
CROSS-SECTIONAL VIEW



D_O = FUEL INLET PORT DIAMETER

D_A = ATOMIZING MEDIA PORT DIAMETER

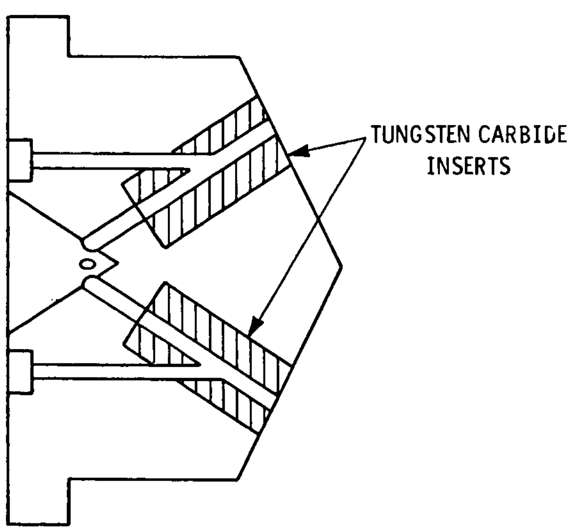
D_M = MIXING CHAMBER DIAMETER

L_{MP} = PRE-MIX LENGTH

L_M = MIXING CHAMBER LENGTH

Figure 8

WEAR RESISTANT ATOMIZER DESIGN



ATOMIZER TEST FACILITY

Figure 9

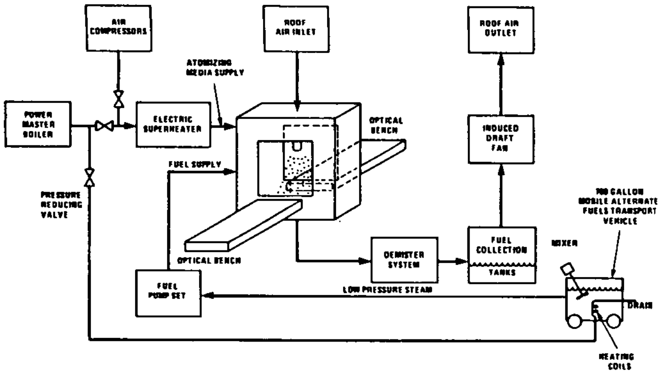


Photo 3

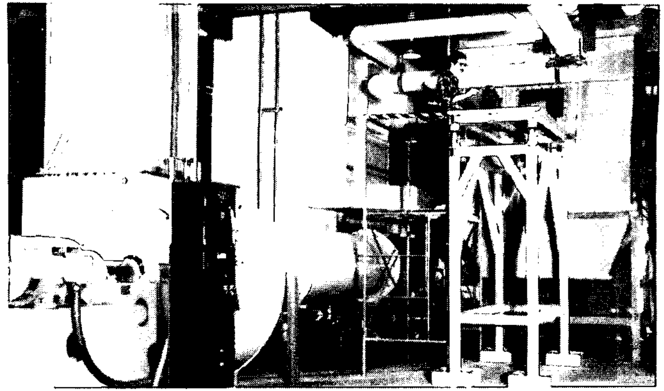
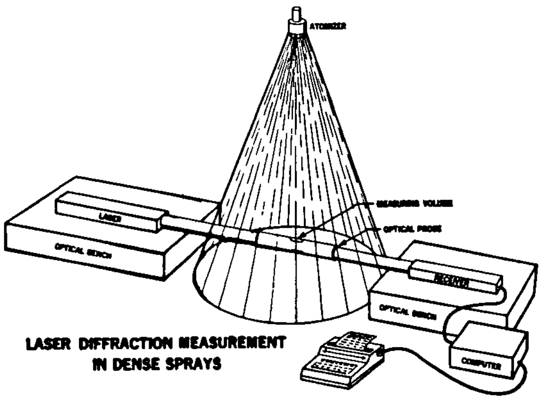
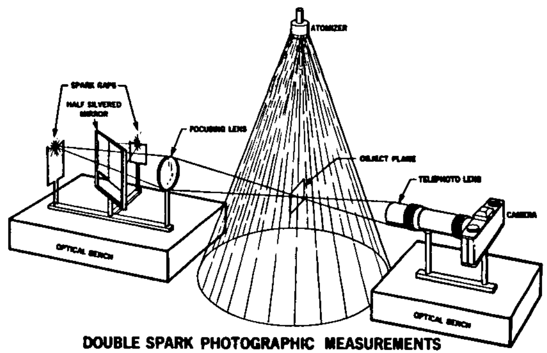


Figure 10



LASER DIFFRACTION MEASUREMENT
IN DENSE SPRAYS

Figure 11



DOUBLE SPARK PHOTOGRAPHIC MEASUREMENTS

Figure 12

INFLUENCE OF ATOMIZER GEOMETRY ON
ATOMIZATION QUALITY
100% LOAD

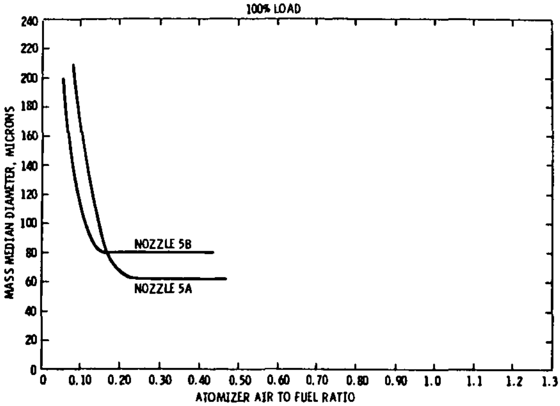


Figure 13

INFLUENCE OF ATOMIZER GEOMETRY ON
ATOMIZATION QUALITY
50% LOAD

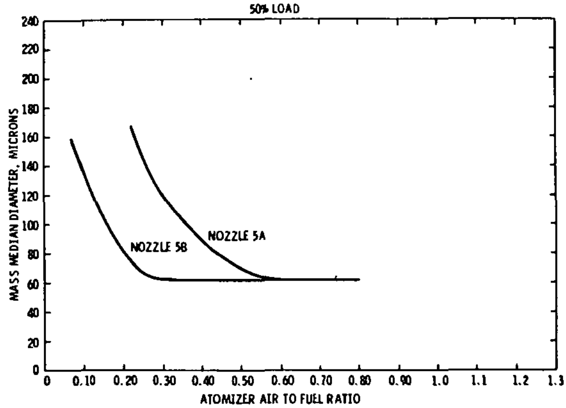


Figure 14

INFLUENCE OF ATOMIZER GEOMETRY ON
ATOMIZATION QUALITY
25% LOAD

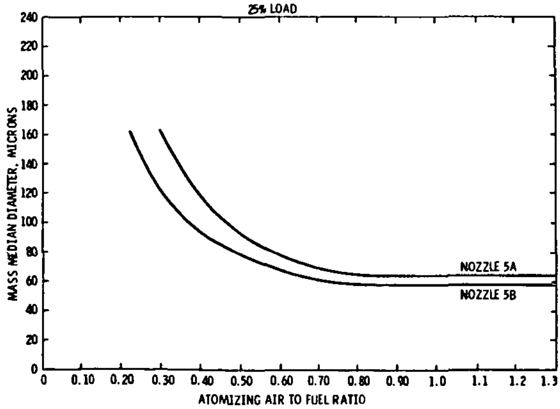


Figure 15

INFLUENCE OF ATOMIZING MEDIA/FUEL MASS
FLOW RATIO ON ATOMIZATION QUALITY
100% LOAD

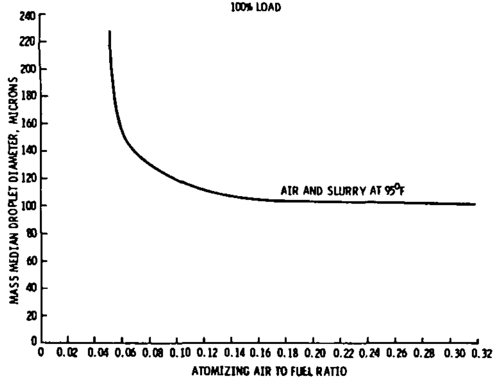


Figure 16

EFFECT OF SLURRY TEMPERATURE

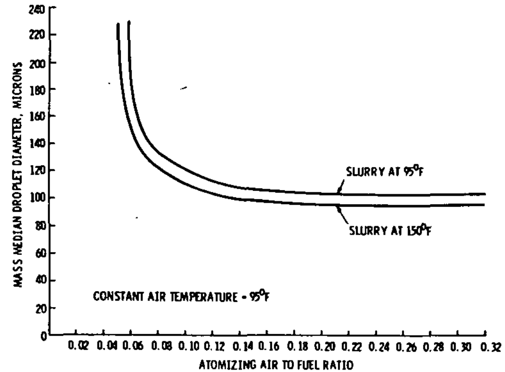


Figure 17

EFFECT OF ATOMIZING AIR TEMPERATURE

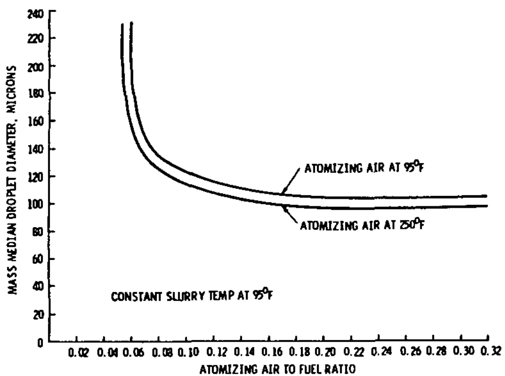


Figure 18

EFFECT OF SLURRY AND AIR TEMPERATURE

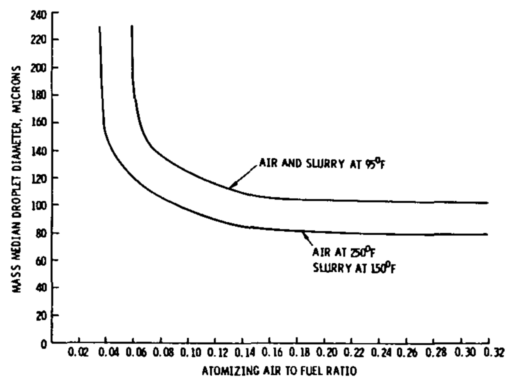


Figure 19

C-E/EPRI CWS BURNER - COLD FLOW MODEL
INDICATED FLAME PATTERN FROM
AERODYNAMICS OBSERVATIONS

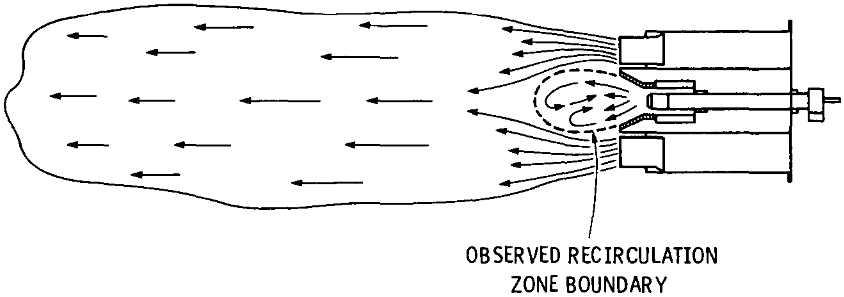


Figure 20

C-E COAL-WATER-SLURRY BURNER SCHEMATIC

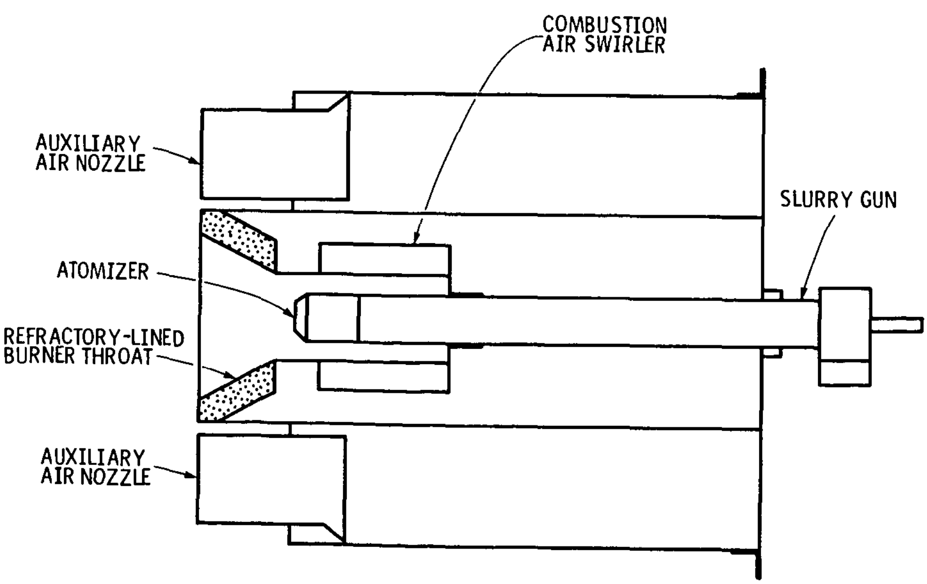


TABLE 3

Coal-Water Slurry Combustion Test Matrix

100% Load = 80 x 10^6 BTU/HR

INDEPENDENT VARIABLES				MEASURED DEPENDENT VARIABLES																ATOMIZER AIR		ATOMIZER PRESS	
TEST NO.	% LOAD	EXCESS AIR	COMB. AIR TEMP.	CO	CO_2	CO_2	NO_x	O_2	STACK SOLIDS LOADING	CARBON BURNOUT	FLYASH SIZE DISTRIBUTION	INSITU FLYASH RESITIVITY	FLAME QUALITY	HEAT FLUX	CALC COMB. EFFY.	FUEL FLOW	COMB. FLOW	AIR TEMP	FLOW	TEMP	FUEL	AIR
1	100	40	250	X	X	X	X	X					X	X	X	X	X	X	X	X	X	X
2	50	40	250	X	X	X	X	X					X	X	X	X	X	X	X	X	X	X
3	25	40	250	X	X	X	X	X					X	X	X	X	X	X	X	X	X	X
4	100	30	250	X	X	X	X	X					X	X	X	X	X	X	X	X	X	X
5	50	30	250	X	X	X	X	X					X	X	X	X	X	X	X	X	X	X
6	25	30	250	X	X	X	X	X					X	X	X	X	X	X	X	X	X	X
7	100	SP	250	X	X	X	X	X					X	X	X	X	X	X	X	X	X	X
8	50	SP	250	X	X	X	X	X					X	X	X	X	X	X	X	X	X	X
9	25	SP	250	X	X	X	X	X					X	X	X	X	X	X	X	X	X	X
10	75	30	250	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
11	75	30	400	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
12	100	30	250	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X

Table 4

Parent Coal Combustion Test Matrix

100% Load = 80 x 10^6 BTU/HR

INDEPENDENT VARIABLES				MEASURED DEPENDENT VARIABLES															
TEST NO.	% LOAD	EXCESS AIR	COMB. AIR TEMP.	CO	CO_2	CO_2	NO_x	O_2	STACK SOLIDS LOADING	CARBON BURNOUT	FLYASH SIZE DISTRIBUTION	INSITU FLYASH RESISTIVITY	FLAME QUALITY	HEAT FLUX	CALC COMB. EFFY.	FUEL FLOW	COMB. FLOW	AIR TEMP
1	100	40	250	X	X	X	X	X					X	X	X	X	X	X
2	50	40	250	X	X	X	X	X					X	X	X	X	X	X
3	25	40	250	X	X	X	X	X					X	X	X	X	X	X
4	100	30	250	X	X	X	X	X					X	X	X	X	X	X
5	50	30	250	X	X	X	X	X					X	X	X	X	X	X
6	25	30	250	X	X	X	X	X					X	X	X	X	X	X
7	100	SP	250	X	X	X	X	X					X	X	X	X	X	X
8	50	SP	250	X	X	X	X	X					X	X	X	X	X	X
9	25	SP	250	X	X	X	X	X					X	X	X	X	X	X
10	75	30	250	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
11	75	30	400	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
12	100	30	250	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X

Figure 21

COMPARISON OF CARBON CONVERSION EFFICIENCY OF PARENT COAL vs COAL-WATER-SLURRY AS A FUNCTION OF EXCESS AIR LEVEL AT 80 x 10^6 BTU/HR

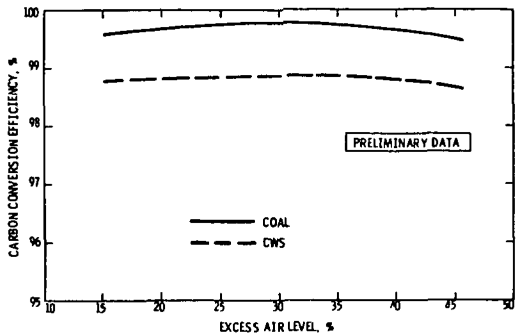


Figure 22

COMPARISON OF CARBON CONVERSION EFFICIENCY OF PARENT COAL vs COAL-WATER-SLURRY AS A FUNCTION OF FIRING RATE AT 30% EXCESS AIR

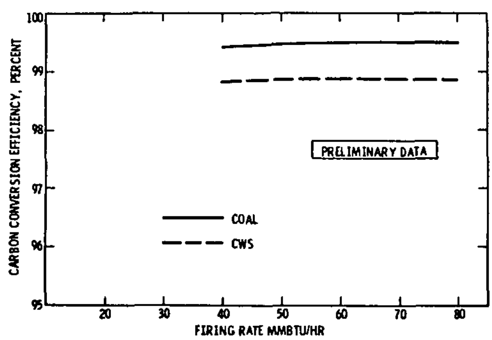


Figure 23

CARBON CONVERSION EFFICIENCY vs ATOMIZING MEDIA RATIO FOR COAL-WATER-SLURRY

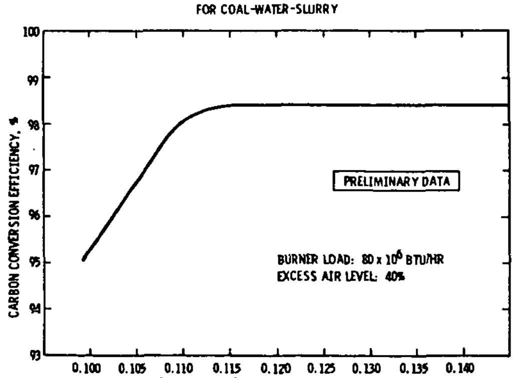


Table 5

FLY ASH RESISTIVITY MEASUREMENTS

FUEL	LOAD (10^6Btu/hr)	EXCESS AIR	COMBUSTION AIR TEMPERATURE (°F)	FLY ASH RESISTIVITY (OMH-CM)
CWS	40	30%	250	1.8×10^8
CWS	60	30%	250	2.1×10^8
CWS	60	30%	400	2.9×10^8
Parent Coal	40	30%	250	2.0×10^8
Parent Coal	60	30%	250	3.7×10^8
Parent Coal	60	30%	400	2.4×10^8
Parent Coal	80	30%	250	3.0×10^8

Table 6

FUEL SYSTEM POWER CONSUMPTION

One Elevation 800 MMBTU/HR Heat Input

(BASED ON LARGE SCALE LABORATORY TESTING)

	Oil (MMBTU/HR)	Coal-Oil (MMBTU/HR)	Coal-Water (MMBTU/HR)
STORAGE	NONE	0.13	0.02
TRANSPORT/FEED	1.71	2.24	2.24
BURNER/ATOMIZER	4.40	5.00	4.60
TOTAL	6.11	7.37	6.86